Gonzalo Seco Granados, nacido en Barcelona en 1972, obtuvo el título de Ingeniero de Telecomunicación por la Universidad Politécnica de Cataluña en 1996, con una nota media ponderada de 10 sobre 10. Por esta misma universidad, en Diciembre de 2000, obtiene el grado de Doctor Ingeniero, con la calificación de sobresaliente cum laude por unanimidad. Su tesis doctoral se centra en el diseño de algoritmos para el uso de arrays de antenas en: i) receptores de los sistemas de navegación GPS y GALILEO, con el objetivo de reducir los errores producidos por la propagación multicamino y las interferencias, ii) receptores de las estaciones base de sistemas de comunicaciones móviles, con el objetivo de aumentar el número de usuarios que se pueden sincronizar y mejorar la precisión del sincronismo. Las contribuciones realizadas han sido publicadas en varias publicaciones internacionales y un capítulo de un libro.

Ha participado en dos proyectos de investigación y desarrollo financiados por la European Space Agency (ESA), relacionados con el diseño de transpondedores para comunicaciones vía satélite, y en otro proyecto del Instituto Nacional de Técnicas Aerospaciales (INTA) y del Instituto de Estudios Espaciales de Cataluña (IEEC), relacionado con el uso de las señales GPS y los satélites MINISAT para la predicción meteorológica. En 1999, realiza una estancia de tres meses en la Brigham Young University (Utah). Durante este tiempo propuso un técnica nueva para la sincronización de señales en escenarios con propagación multicamino e interferencias direccionales. En 2001, realiza una estancia de tres meses en la empresa Winphoria Networks (Madrid), y pasa cuatro meses en la Columbia University (New York). En Winphoria Networks analizó proyectos de inversión para operadores móviles interesados en adaptar sus redes a sistemas de 3G. En la Columbia University, se especializó en finanzas. Desde octubre de 2000, ha estado cursando un MBA en el Instituto de Estudios Superiores de la Empresa (IESE), perteneciente a la Universidad de Navarra en Barcelona. Sus líneas de interés están alrededor del procesado digital y estadístico de señal, diseño de receptores para sistemas de navegación (GALILEO) y algoritmos para el posicionamiento, nivel 1 y 2 de sistemas de comunicaciones móviles indoor y outdoor, teoría de la estimación, instrumentos derivados y mercados de capitales.

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Summary of the PhD Thesis:

"Antenna Arrays for Multipath and Interference Mitigation in GNSS Receivers"

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Abstract

Esta tesis aborda la sincronización de una o varias réplicas de una señal conocida recibidas en un entorno con propagación multicamino e interferencias direccionales. Uno de los hilos conductores de este trabajo es la aplicación sistemática del principio de máxima verosimilitud (ML, maximum likelihood en inglés) junto con un modelo de señal en el cual las firmas espaciales no tienen estructura, y en el cual el ruido es Gaussiano y presenta una matriz de correlación desconocida. Esta última suposición es fundamental a la hora de obtener estimadores capaces de atenuar las señales interferentes que presentan algún tipo de estructura, y esto se consigue sin necesidad de recurrir a la estimación de ciertos parámetros de dichas señales. Por otra parte, la suposición de que las firmas espaciales carecen de estructura tiene ventajas desde un punto de vista práctico, al mismo tiempo que simplifica la estimación del resto de parámetros ya que las estimaciones de estas firmas se pueden calcular de forma cerrada. Esto constituye un primer paso hacia la eliminación de las búsquedas en múltiples dimensiones, que es otro de los objetivos perseguidos en este trabajo. En todos los casos, las prestaciones de los diferentes estimadores que se proponen a lo largo de la tesis se estudian rigurosamente, y tanto de forma comparativa (o sea, con respecto a otros estimadores existentes) como de forma absoluta (o sea, comparándolas con el Cramér-Rao Bound –CRB). Por esto, también se ha derivado el CRB para cada uno de los modelos de señal utilizados en la tesis.

En la primera parte de la tesis se deduce la solución de máxima verosimilitud para el problema general de estimación de retardos cuando el ruido tiene correlación espacial desconocida. Se demuestra que el criterio resultante para los retardos es consistente y asintóticamente eficiente, pero también es altamente no-lineal debido a la presencia del determinante de una matriz y no permite, por tanto, el uso de procedimientos sencillos de optimización. Asimismo, se demuestra y se argumenta intuitivamente que el criterio óptimo ML se puede aproximar por una función de coste más sencilla que es asintóticamente equivalente. A diferencia de otros problemas de estimación, en el caso tratado aquí, el primer término del desarrollo de Taylor del estimador ML no conserva la eficiencia asintótica, y en esto radica justamente la dificultad del problema. La característica esencial de la nueva función de coste es que depende linealmente de la matriz de proyección sobre el subespacio de las señales y, por lo tanto, admite ser minimizada mediante el algoritmo IQML, que es eficiente desde el punto de vista computacional. Además, la existencia de métodos de inicialización sencillos y robustos a las interferencias, los cuales se basan en el uso de una matriz de pesos igual a la identidad y posiblemente también en el algoritmo ESPRIT, hace que el esquema de estimación propuesto pueda ser viable para un diseño práctico. La nueva función de coste se puede aplicar de la misma manera a la estimación del retardo en un canal FIR. En este caso, el algoritmo IQML se puede modificar de forma que, en cada iteración, la estimación del retardo se obtiene a partir de las raíces de un polinomio cuyo orden es igual a dos veces la longitud del canal.

El objetivo perseguido por los estimadores presentados en la segunda parte de la tesis es aprovechar una particularidad de los sistemas GNSS (Global Navigation Satellite Systems), que consiste en que la dirección de llegada de la señal directa puede ser conocida a priori. Basándose en esta información adicional y suponiendo que el array está calibrado, se propone un modelo simplificado,

aunque al mismo tiempo aproximado, para la señal recibida. En este modelo todas las señales excepto la señal directa se engloban en un término con correlación espacial desconocida. Se analizan los estimadores ML del retardo y de la fase de portadora de la señal directa. El sesgo producido por las componentes multicamino (normalmente la principal fuente de errores en aplicaciones GNSS) se reduce en estos estimadores de forma muy importante con respecto al sesgo que sufren otros métodos. De hecho, el error cuadrático medio de los estimadores propuestos es en muchas ocasiones muy próximo o incluso inferior al mínimo error que se puede alcanzar con modelos más detallados del canal multicamino. Asimismo, se presentan dos algoritmos de estimación del retardo basados en el cálculo de las raíces de un polinomio. Se demuestra también que las estimaciones ML se pueden obtener a partir de la señal de salida de un conformador de haz híbrido. Debido a que el propio conformador depende de las estimaciones del retardo y de la amplitud de la señal directa, el uso de un algoritmo iterativo surge de forma natural. La formulación mediante el conformador híbrido proporciona una interpretación alternativa interesante de la estimación ML, y podría ser apropiada para una realización práctica. Finalmente, se demuestra analíticamente y numéricamente que el estimador propuesto para el retardo es robusto frente a errores en el valor nominal del vector de enfoque de la señal directa, y se presenta una manera de extender el margen tolerable de errores de apuntamiento.

En la última parte de la tesis se trata la sincronización de un usuario deseado que transmite una secuencia de entrenamiento conocida en un sistema de comunicaciones DS-CDMA. El modelo de señal utilizado agrupa el ruido, y la interferencia externa y de acceso múltiple en un término de ruido equivalente que presenta una matriz de correlación espacio-temporal desconocida. Partiendo de este modelo, se deduce un estimador del retardo que es una aproximación para un número grande de muestras del estimador ML exacto y que es apropiado para canales con desvanecimientos lentos y no selectivos en frecuencia. El estimador propuesto es una técnica de un solo usuario y es resistente al efecto near-far. Su importancia radica en el hecho de que aprovecha la estructura de las señales en el dominio temporal y espacial, lo que contrasta con otros métodos existentes que, a pesar de utilizar un array de antenas, sólo utilizan la estructura de las señales en uno de los dos dominios. En un sistema de comunicaciones móviles, el usuario deseado está interferido por un número generalmente elevado de señales de otros usuarios y por posibles interferencias externas. En concordancia con este hecho, los resultados numéricos han mostrado que el uso conjunto de todos los grados de libertad espacio-temporales es indispensable para la correcta sincronización en sistemas con una carga elevada de usuarios y/o en presencia de interferencias externas.

1. Introduction

The focus of this thesis is on the use of antenna arrays for the synchronization of a known signal in the presence of multipath propagation and directional interference. The initial framework of this work was the positioning systems. Notwithstanding, synchronization is a rather general problem, common to communication, radar and sonar systems. Therefore, the general design criteria, initially tailored to positioning systems, have been extended in order to derive synchronization methods also for communications systems. In the sequel, the problems associated with both types of systems are introduced, and subsequently the objectives of the thesis are described.

1.1. Positioning systems

Global Navigation Satellite Systems (GNSS) complement and will probably replace in a near future all other positioning, navigation and synchronization systems. At the present time there are two such systems being operative: GPS (Global Positioning System) and GLONASS (the Russian space-based radionavigation system). Plans are being conducted for the deployment of the future system called GALILEO. All these systems share the same operating principle, that is, the receiver position is computed by determining the distances from the receiving antenna to a set of satellites.

The receiver determines these distances by measuring the propagation time of each satellite's signals, which can be obtained from the delay (referred to as pseudorange or code phase) of the equivalent baseband signal and also from the carrier-phase.

The surprising evolution of GNSS applications has lead to stringent requirements for GNSS receivers, particularly in regard to their accuracy. Augmentations such as differential operation help to reduce or eliminate many sources of errors (e.g. common-mode atmospheric, orbit and satellite errors), but multipath remains the dominant error source in most high precision applications and is the limiting factor in achieving the ultimate GNSS accuracy. Due to the operating principle of the GNSS systems, the direct signal (also designated line-of-sight signal or LOSS for short) is the only one that bears useful information about the distance between the receiver and the satellite. Significant research and development efforts have been devoted to the mitigation of multipath, and several techniques have been proposed up to now. They may be classified following a variety of criteria: real-time versus post-processing techniques, multiple versus single antenna techniques, etc. Besides, like any other system, GNSS may also be exposed to external interferers, which have to be cancelled in the receiver in order to make GNSS adequate for many safety-critical applications, such as automatic guidance and landing systems. Several methods can be used to mitigate narrow-band interferences in single-antenna receivers. However, single-antenna methods cannot combat wide-band interferences.

The errors in the pseudorange and carrier-phase measurements produced by the multipath propagation have been studied in several papers. Only the reflections that are correlated with the direct signal, which are usually referred to as coherent multipath, are responsible for these errors; and this is the type of reflections considered in this thesis. Their main characteristic is that their relative delay with respect to the LOSS is on the order of or smaller than the inverse of the signal bandwidth. The most widespread multipath-mitigation techniques are those based on modifications of the conventional delay locked loop (DLL), which is the synchronization method used in the vast majority of GNSS receivers. For instance, in a GPS receiver endowed with a DLL, the multipath components may bias the pseudoranges in several tens of or even a hundred of meters, what at the same time hampers the ambiguity resolution process needed for carrier-phase ranging. The biases in the carrier-phases (unrealistically assuming perfect ambiguity resolution) may reach some centimeters. Some of those modifications are the Narrow Correlator DLL, the Multipath Estimating DLL (MEDLL, patented by NovAtel Inc.), and the edge- and strobe-correlator technology (patented by Astech Inc.). These single-sensor techniques can discriminate the line-of-sight signal from the reflections only in the temporal domain, and their performance is still inadequate for many precise applications. This is why the use of antenna arrays in GNSS receivers seems to be a very promising approach. Together with the previous real-time signal processing methods, some post-processing approaches for multipath mitigation have appeared in the literature. Since these techniques require data recording for several minutes or hours, they are restricted to a small number of applications.

1.2. Communication systems

Precise synchronization is not only the key to obtaining location estimates with accuracies of a few meters or better in GNSS receivers, but also a critical aspect of virtually all communication systems. Accurate frame and symbol synchronization is especially important in time-division multiple access (TDMA) and packet-based systems, or code-division multiple access systems (CDMA). Timing information is also needed for any other application where range measurements are made, as in active radar and sonar systems. In these fields the problem is usually referred to as propagation delay or time delay estimation, but in mathematical terms there is little difference between this and synchronization.

The last part of this thesis addresses the problem of synchronization of DS-CDMA wireless communication systems, which use the same modulation format as present positioning systems. Multiple-access interference (MAI) is inherent to asynchronous DS-CDMA systems, since orthogonality among the users' codes cannot in general be achieved. The MAI can make the conventional detector (i.e., a bank of filters, each matched to a specific user's code) become useless when the powers of the signals received from different users are unequal. This is the so-called near-far problem. One alternative to overcome this problem is the use of power-control schemes. However, these schemes have some limitations because they increase the overall complexity of the system, do not guarantee an optimal performance (e.g., they limit the performance of users with good channels, and some cross-talk still occurs even though power control is used), and there are certain system configurations in which a proper power control cannot be employed (e.g., when several receivers are used). The use of multi-user detectors is, therefore, necessary in most communication systems in order to combat the near-far problem. The optimum receiver proposed by Verdú in 1986 has been followed by a number of sub-optimum ones. All these receivers require the knowledge of one or several parameters, such as the users' code timings, powers and carrier phases. Moreover, the code timings generally need to be estimated with high accuracy, since errors thereof have large impact on the performance of many detectors. The employ of near-far resistant and accurate code synchronization techniques for acquisition and tracking is therefore essential to achieve a correct performance in a DS-CDMA system. Some papers stating that the capacity of a DS-CDMA system is limited by the ability to achieve code acquisition corroborate this statement. Besides, MAI is not the only type of interference that may be received. The receiver can be disturbed by any other intentional or fortuitous signal, which we will denote in general as external interference. Consequently, the design of synchronization techniques that are also robust against external interference is of fundamental importance in many situations. There is a vast literature on time delay estimation, the majority of which focuses on the case where the data is measured from a single antenna. However, the performance of single channel timing recovery methods is limited when multipath or co-channel interference (CCI) is present, such as in many wireless communications applications. For this reason, attention has recently shifted to the use of antenna arrays for addressing these problems. The spatial selectivity offered by an antenna array can dramatically improve the performance in environments with severe CCI.

1.3. Synchronization using Antenna Arrays

Spatial filtering is probably the most effective approach to overcome the limitations of the single-antenna multipath mitigation techniques and to cancel wide-band interferences. Indeed, using antennas with special reception patterns (choke rings) and locating them wisely have been, among the GPS community, the traditional ways of filtering out spatially the undesired signals. A much more powerful alternative is to employ adaptive arrays of antennas.

However, the use of adaptive antenna arrays in GNSS receivers has not been deeply studied, and most of the few approaches appeared in the literature have centered on interference mitigation. Some papers have applied the well-known minimum variance distortionless response (MVDR) beamformer and the power inversion (or linear prediction) beamformer. When these two beamformers are applied directly to the received signals, they cancel the interferences but not the reflections of the GNSS signal, which are well below the noise floor. A broad-band combiner structure has been proposed by other authors and employed in order to cancel the narrow-band interferences in the temporal domain and the wide-band ones in the spatial domain.

An early paper of the author showed the significant benefits of using an antenna array to combat both the interferences and the multipath in a GNSS application. In order to cancel both types of disturbing components, the array processor has to operate with the received signals after the despreading. Sometimes the design of an appropriate beamformer comes down to a DOA estimation problem, which is a challenging task in coherent scenarios. The high degree of coherence between the LOSS and the reflections makes conventional DOA estimation algorithms completely fail. There are algorithms that work properly with coherent sources but they have several drawbacks: high computational load, they can only cope with specular multipath, and the number of received signals has to be bounded by the number of antennas. Moreover, the performance of the methods based on DOA estimation is suboptimal since they do not exploit the temporal structure of the signals. The methods developed in this thesis aim at overcoming all these drawbacks and also the limitations of the spatial smoothing technique.

A different method consists in estimating the parameters a single reflection which tries to model all the actually received reflections. To this end, the actual phase evolution along the aperture is compared with the theoretical phase evolution when only the LOSS and one reflection are received, assuming that the direction of arrival of the direct signal and the array attitude are known. Since this algorithm deals with the phases, and possibly pseudoranges and SNR measurements, instead of the received signals, the estimation process is highly non-linear; and it is not a signal processing technique but data processing one. Moreover, it does not mitigate interferences.

Unlike navigation systems, lately the employ of antenna arrays in wireless communication systems has arisen great interest since the multiple benefits they provide ultimately result in an improvement of the system capacity, coverage and quality. A number of techniques that exploit antenna arrays for synchronization have been developed, each differing from the others on its assumptions regarding multipath, CCI (co-channel interference), signal parameterization, and computational load. Some researchers have taken a parameter estimation point of view, attempting to determine the direction of arrival and time delay of each arrival of a given signal at the array. These techniques exploit the full space-time structure of the multipath, but many of them do not take CCI into account.

A maximum likelihood (ML) approach is taken in other work, in which both the interference and noise are modeled together as a temporally white Gaussian process. Some methods also assume spatial whiteness, and very few of them are able to combat the CCI. The conceptual resemblance between the space-time manifold and the space-only manifold employed in DOA estimation problems makes straightforward the extension of some DOA estimators to the delay-DOA estimation problem. Another alternative is to solve the joint angle and delay estimation problem via weighted least squares (WLS), where the weighting matrices are designed to account for spatial color, array calibration errors, etc. While offering some claim to optimality, the primary drawback of the ML and WLS approaches is that complicated search procedures are required to estimate the desired parameters.

To obtain DOA estimates of each arrival, the parametric approaches must assume the availability of a calibrated antenna array, and a single arrival at each time delay. Errors in the array calibration or deviations of the array from uniformity are inevitable, and can lead to significant performance degradation. Furthermore, in multipath-rich propagation environments, there may be numerous arrivals at each delay due to local scattering near the array. To overcome these difficulties, an unstructured parameterization of the spatial response can be used. While this leads to an increase in the number of parameters to be estimated, the model is linear in the additional parameters, and they can be estimated in closed form. Note however that these techniques assume spatially and temporally white noise, and thus are not suited for situations involving strong CCI. Other work has focused on the special nature of the synchronization problem in various applications. One example is the use of antenna arrays in code timing recovery for CDMA systems, where an approach that estimates the code timing for one user at a time while treating the multiple access CCI as Gaussian interference with unknown spatial color has been proposed in this thesis.

1.4. Objectives of the Thesis

Due to the limitations of the multipath and interference mitigating techniques proposed to date for GNSS receivers, we have found interesting to further investigate new methods to combat those error sources. We argue the shortcomings of the single-antenna methods, and the use of an antenna array in the receiver is proven as a highly effective alternative because arrays can exploit the virtually sole diversity source, that is spatial diversity, present in GNSS scenarios subject to coherent multipath propagation. Therefore, the overall objective of this thesis is to study and propose estimators of the unknown parameters (time delay, and carrier phase or spatial signature) of the incoming signals when an antenna array is used in the receiver, and multipath components and interferences are present. Given the increase of the receiver complexity introduced by an antenna array, it is worth investigating techniques that exploit efficiently the use of the array and thus are able to combat those two main disturbing effects, and not only one of them like many previous works. Note that we focus on signal processing techniques and not on data/observables processing methods. The common thread of all the proposed estimators is that they are derived using the Maximum Likelihood (ML) principle and assuming an arbitrary unknown correlation of the noise. The ML principle is one of the chief systematic approaches to many estimation problems. While ML estimators are often readily derived, they usually lead to excessively complex problems. Therefore, interest is placed in obtaining, either systematically or ad hoc, simpler techniques that may be viable for practical implementation.

In order to overcome the limitations of many existing methods, an initial premise was to impose no restrictions on the array geometry, along with reducing as much as possible the number of variables of the resulting cost functions. The parameters that are not of interest in our application have to be modeled in such a way that their contribution can be eliminated in closed form. This refers especially to the directions-of-arrival (DOA) of the signals. Hence, the estimators do not have to rely on DOA estimation procedures. The effort invested in estimating the DOAs, which would be very important because spatial searches are generally needed, could hardly be justified since the parameters of interest in a GNSS application are not the DOAs themselves. Another objective is the exploitation of a particularity of GNSS systems consisting in that the positions of the transmitter and the receiver are approximately known. This has made possible the derivation of a technique able to combat specular and diffuse multipath.

The methodology of derivation of ML estimators can be also applied to DS-CDMA communication systems. However, there are some important differences between communication and navigation systems. In the latter, the focus is on combating the reflections of the direct signal, in addition to the external interferences. Since the number of external interferences is assumed small or comparable with the number of antennas, it is possible to largely mitigate those interferences using only the spatial degrees of freedom, which is related to considering that the noise is correlated only in the spatial domain. Whereas, in CDMA communications systems, the signal of a desired user is interfered by the signals of a large number of users. Since the number of disturbing signals usually exceeds the number of spatial or temporal degrees of freedom separately, it is necessary (at least in heavily loaded systems) to employ jointly all these degrees to combat the MAI. Hence, the signal model has to be modified in order to take into account the space-time correlation of the interference.

The contributions of this thesis have been divided into three parts, corresponding each one to one chapter (chapters 3,4 and 5). The first addresses a general time delay estimation problem, whereas the other two consider signal models that are tailored to a GNSS receiver and to a DS-CDMA multiuser communications receiver. Below we summarize the main contributions in each of these parts.

2. Time Delay Estimation of Multiple Replicas of a Signal

The goal pursued in the third chapter is to present an asymptotically efficient approximation to the maximum likelihood estimator of the time delays of multiple replicas of a known signal received in a noise field with unknown spatial correlation. Several ways of deriving the new estimator are presented, and its performance is analyzed theoretically and using simulation results. The form of this estimator makes possible the use of computationally appealing optimization algorithms.

In this first part, we have focused on how multiple antennas can be efficiently used in interference-limited scenarios in order to estimate the time delays of multiple replicas of a known signal. A number of techniques have been proposed in the literature for the estimation of the parameters of a multipath channel. In general, the existing techniques present at least one of the following drawbacks: *i)* the resulting multidimensional criteria require computationally demanding optimization procedures, *ii)* the techniques undergo a severe degradation in the presence of directional interference in spite of using an antenna array in the receiver because it is assumed that the noise is spatially white. It was recently shown that the first of the drawbacks can be overcome by assuming that the spatial signatures are deterministic unstructured vectors and that the noise is Gaussian, and spatially and temporally white. Thus, the time delay estimation problem becomes analogous to the DOA estimation problem with uniform linear arrays, and computationally efficient algorithms, such as IQML and ESPRIT, can be applied. The goal pursued in this part of the thesis is to overcome also the second drawback. To this end, the noise is assumed to have an arbitrary and unknown spatial correlation, in such a way that the resulting estimators are robust against the co-channel interference.

Under the assumption that the noise and CCI are spatially colored but temporally white Gaussian processes, and that the spatial signatures are unstructured, the maximum likelihood solution to the time delay estimation problem was derived. It was proven theoretically that the ML estimator is consistent and asymptotically efficient. However, the resulting concentrated ML criterion for the delays is highly non-linear due to the presence of a determinant operator. It is no longer possible to draw parallels between this estimator and the conventional maximum likelihood DOA estimator, and hence the ML time delay estimator does not lead to simple minimization procedures. Using various systematic and heuristic techniques, it was shown how the optimal ML criterion could be approximated by a simpler cost function that was shown to provide asymptotically equivalent (and hence statistically efficient) delay estimates. This new estimator constitutes the main contribution of the first part of the thesis. The proof that the new method is equivalent to the ML criterion relies on the verification of a condition related to the asymptotic behavior of both estimators. Three intuitive explanations of the equivalence are provided. The first one is based on the Taylor series expansion of the logarithm. The second one explores the differences and similarities of the geometric and arithmetic means, which are closely related to the differences and similarities between asymptotically efficient and consistent-only estimators. The third explanation presents a trick that makes a first-order Taylor expansion useful for the problem at hand. The interpretation of the new estimator is also very appealing, because it resembles the estimator for the white-noise case with the difference that previously the signals have been prewhitened using an estimate of the noise correlation. A consistent and robust estimator is proposed to obtain this estimate of the noise correlation needed by the asymptotically efficient estimator.

The essential fact is that the form of the new criterion lends itself to minimization by the IQML algorithm, an iterative approach that avoids the need for gradient-based or exhaustive searches. The existence of simple yet accurate initialization schemes based on ESPRIT or identity weightings makes the approach viable for practical implementation. There is evidence that other researchers had been searching unfruitfully an estimator with such properties. We were the first ones in proposing it, and this represented a remarkable success among the signal processing community. Two different procedures to implement the IQML algorithm in the new cost function were discussed. The one that updates the noise correlation matrix at each iteration of the IQML algorithm (named coupled-iterations method) is preferred. A number of simulation studies were presented that demonstrate the performance advantage of the proposed technique over related delay estimators, and also analyze its optimality in the finite-sample case by comparison with the Cramér-Rao bound (CRB). Only as an illustrative example, the performance of the proposed estimators is shown in the following figure. As predicted by the theoretical study, the RMSE of $g(\tau, \mathbf{W})$ tends to the CRB as the number of samples increases. The cost function $g(\tau, \mathbf{I})$ performs much better than the estimator designed for the white-noise case, which was the estimator available before the publication of the results in this thesis, and serves as an excellent initialization method.

Finally, the new cost function was also applied to the estimation of the frame delay in a FIR channel We proposed for this case a formulation of the projector onto the orthogonal complement to the signal subspace that reduced each iteration of the IQML algorithm to the rooting of a polynomial, being its order equal to twice the length of the FIR channel. The result is a iterative feedforward scheme for frame delay estimation.

The contributions of this part of the thesis have been published in the references 3,4,6 and 8 of the list of publications.

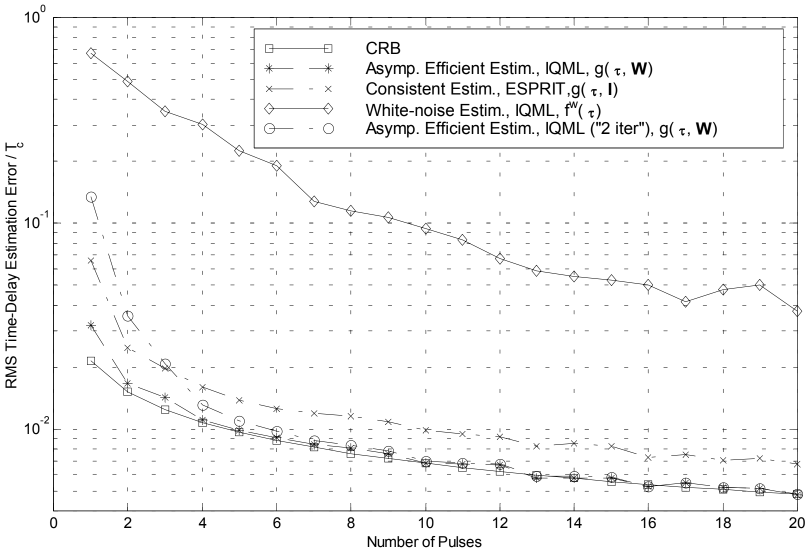

Figure 1: RMSE of the proposed estimators as a function of the number of pulses. Parameters: θ_0=0º, θ_1=10º, θ_i=-30º, τ_0=0, τ_1=0.4T_c, m=6 antennas, SNR_0=15.87dB, SIR_0=-3.13dB, SNR_0/SNR_1=3dB.

3. Time Delay and Carrier Phase Estimation of One Replica with Known Steering Vector

The objective of the estimators presented in the second part of the thesis was to take advantage of one particularity of GNSS systems, which consists in that the DOA of the line-of-sight signal may be known a priori. As long as the antenna array is calibrated, the knowledge of this direction-of-arrival allows us to compute beforehand the steering vector of the direct signal, which acts as a spatial reference to this signal. It is shown that the use of the steering vector of the LOSS is not expected to provide a significant performance improvement of the ML estimators derived using a detailed model of the multipath channel (i.e. the model used in the first part of the thesis). And, what is worse, the resulting estimators are highly nonlinear and cannot be approximated by computationally simpler ones. Therefore, that additional information is employed to set up a simplified and approximate model, in which all signals excepting the direct one are modeled as a Gaussian term with unknown and arbitrary spatial correlation matrix. The ML estimators of the time delay and carrier phase of the direct signal were derived using this simplified model.

The estimator presented in this part of the thesis outperforms the estimators obtained with additional simplifying assumptions, such as that the noise field is spatially white or that the spatial signature of the direct signal is unknown (see Figure 2). Actually, it is shown that the proposed ML cost function is the quotient between the ML cost function obtained at the output of the minimum variance beamformer and the ML cost function obtained without knowledge of the steering vector of the direct signal. Figure 3 shows the shape of the cost functions involved. It is clear that the ML cost function we have proposed inherits the best characteristics of the other two functions. One of them identifies all the components of the received signal (i.e. presents one peak for the LOSS and for each reflection), while the other cost function selects the peak corresponding to the LOSS and places nulls at the peaks corresponding to the reflections. Thus, the ML cost function presents a single peak located at or very near the delay of the direct signal. Moreover, the performance of the proposed ML estimator is in many situations very close to or even superior to the best possible performance of more complex methods based on an exact description of the multipath channel (see Figure 2). This is a remarkable result taking into account that the technique has low complexity because only the parameters of the line-of-sight signal are estimated. In particular, the ML estimator is robust against arbitrarily strong interferences and reduces in several orders of magnitude the errors produced by the reflections of the GNSS signal. This proves that although the simplified model is approximate in the presence of reflections, as long as it is combined with a spatial reference to the line-of-sight signal, it makes possible the derivation of an estimator that mitigates interference- and multipath-induced errors, and offers an excellent trade-off between bias and RMSE for highly coherent reflections. Furthermore, this estimator is applicable identically in the presence of any type (specular or diffuse) of multipath, which is another advantage with respect to methods based on the exact description of the multipath channel.

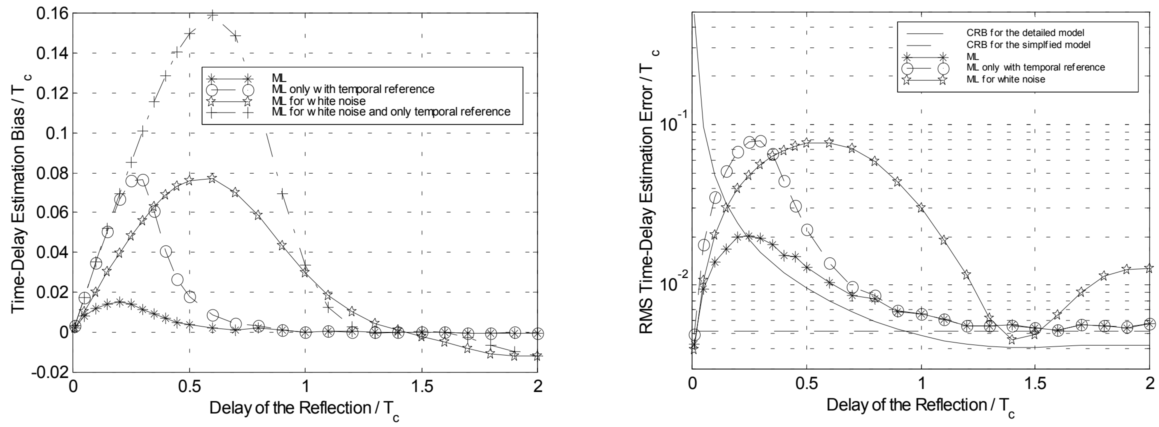

Figure 2: Bias and RMSE of the time-delay produced by one reflection as a function of its delay relative to the direct signal. Parameters: θ_0=0º, τ_0=0, θ_1=10º, $\alpha_0/\alpha_1=sqrt(2)$, M=3 pulses, m=6 antennas, SNR_0=15.87dB.

Two polynomial-rooting algorithms for computing the time delay estimate were presented. The first exploits the linear-phase dependence on the delay of the frequency samples of the signal and involves polynomials of relatively large order, while the second employs a simple linear interpolation of the signal vector and the polynomial to be rooted is quadratic. The equivalence between the maximum likelihood estimation and a specific type of beamforming is also presented. Not only does this equivalence shed light on the performance of the systematic, yet not very intuitive, ML estimators of the code and carrier phases presented previously, but it is also the basis for an iterative and practical implementation of those ML estimators. From the beamforming viewpoint, the cost function to be optimized has a clear interpretation, and can be written without the need of a probabilistic description of the data. Thus, it is easier to understand how the signals received at different antennas are processed in order to mitigate the effects of the undesired components. However, no a priori claims for the optimality of the estimates obtained from the beamforming approach can be done. On the other hand, the maximum likelihood principle provides a procedure to obtain “optimum” estimates (in the sense that usually they are asymptotically efficient) based on a probabilistic setting, but sometimes it fails in giving an understandable interpretation about how the signals are processed. The beamformer that allows us to obtain the ML estimates is a hybrid beamformer, which is computed iteratively as a weighted linear combination of the minimum variance beamformer and the temporal reference beamformer. The hybrid beamformer performs much better than its two components in scenarios with multipath propagation. An example of the excellent performance of the ML estimator and the convergence of the iterative hybrid beamforming algorithm in a scenario with diffuse multipath is shown in Figure 4. Finally, it is remarkable that the relationship between the ML estimator and the hybrid beamformer offers an interesting view of the estimation process, since it separates in two different, yet coupled, stages the spatial filtering and the temporal processing.

We have also been able of deriving expressions for the asymptotic variance of different estimators. These results prove that the ML time delay estimator, unlike the estimator based on the minimum variance beamformer, is inherently robust against errors in the nominal steering vector of the direct signal. Finally, a modification of the ML estimator that further extends the range of tolerable pointing errors has been presented. It is based on averaging the original estimator according to the uncertainty (i.e. probability density function) in the nominal steering vector.

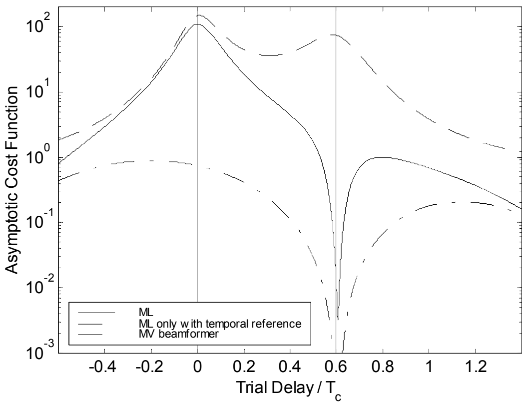

Figure 3: Asymptotic shape of the cost functions. Parameters: θ_0=0º, τ_0=0, θ_1=10º, τ_1=0.6T_c, α_0/α_1=$sqrt(2)$, M=∞ pulses, m=6 antennas, SNR_0=15.87dB.

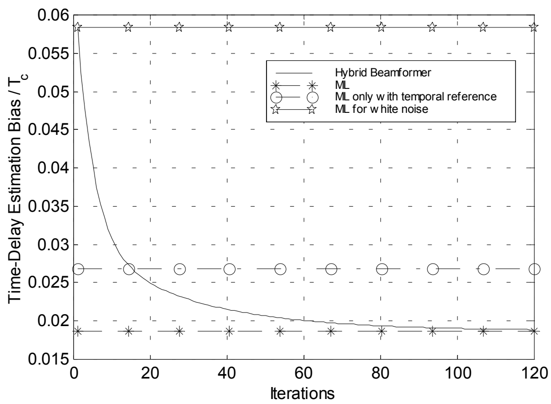

Figure 4: Performance of the ML estimator and convergence of the time-delay estimates obtained from the iterative hybrid beamformer in an scenario with multiple reflections.

The contributions of this part of the thesis have been published in part in the references 2,10,11, 12, 14 and 15 of the list of publications.

4. Code-Timing Synchronization in DS-CDMA Communication Systems Using Space-Time Diversity

In the last part of thesis the synchronization of a desired user transmitting a known training sequence in a direct-sequence (DS) asynchronous CDMS system has been addressed. A code-timing synchronization technique that operates in near-far, frequency-nonselective, slowly fading channels and employs an arbitrary antenna array for reception has been derived by applying the ML principle. The technique is a large sample approximation of the exact ML estimator. We have taken into account the fact that the signals of the users present definite space-time signatures, what happens because the observation interval is usually much smaller than the correlation length of the channel. As such, the proposed technique is a single-user, near-far resistant estimator and would be applicable in a system employing multiuser detection without power control. For the derivation, it has been assumed that the desired user transmits a known training sequence, and all other received components (e.g., multiple-access interference, external interference and noise) have been modeled as a Gaussian term with unknown space-time correlation. The main contribution of the approach presented in this part of the thesis is that it fully exploits the spatial and temporal structure of the interfering signals in order to cancel them. This allows both the temporal (provided by the codes) and spatial (provided by the antenna array) of the received signals to be exploited. The knowledge of the spreading waveform (code) of only the desired user is needed, and as a by-product, an estimate of the spatial signature of this user is obtained.

Previous work of other authors assumed that the interfering signals were uncorrelated among antennas, and hence the methods derived under that model reduced themselves to several single-sensor estimators applied in parallel to several independent channels. The effect of the antenna array was only to increase the signal-to-noise ratio and to provide diversity in order to combat the fading of the desired user's signal at different antennas (i.e., maximal ratio combining); but the array did not use the directional properties of the interfering signals in order to cancel them. Indeed, as pointed out by those authors themselves, the performance of those estimators could not be significantly improved by increasing the number of antennas when, for fair comparisons with single-antenna methods, the interference power was proportional to the number of sensor used in the receiver. On the other hand, other authors assumed that the interference was correlated among antennas but white in the temporal domain. While the methods proposed by authors used the spatial structure of the multiple-access-interference to combat it, they needed a prohibitively large number of antennas to achieve near-far resistance. The benefits in symbol detection of exploiting the joint space-time signature had been analyzed thoroughly in the literature, but the use of the space-time signature in synchronization remained as an open issue. The estimator derived in the thesis contrasts with other methods put forward up to date that also employ antenna arrays but only exploit the structure of the signals in one of the domains. As a result, the proposed technique outperforms existing synchronization methods for reasonable lengths of the training sequence and reasonable sizes of the array (see Figure 5). This technique allows to allocate more users than the value the spreading factor of the modulation, and makes possible the coexistence of the DS-CDMA communications system with other wide-band (and also narrow-band) interfering sources. We have also discussed that the use of a structured estimate of the correlation matrix or diagonal loading allows to reduce the required size of the observation interval, and provides a better performance than the pseudo-inverse approach. This is a contribution to the application of the ML principle with singular or ill-conditioned correlation matrices. The RMSE and the acquisition probability of the proposed algorithm have been evaluated numerically in two types of channels. Although the estimator is applied in a multiple-access scenario, the RMSE attains in the static channel the CRB derived under the Gaussian assumption, which confirms the validity of the starting model. All the analyzed estimators are deteriorated when the channel presents Doppler and angular spread, but also in this situation, the estimator proposed herein outdoes the other ones. The results of this part of the thesis conclude that the efficient use of the space-time diversity is indispensable for the correct acquisition and tracking of the synchronization parameters in heavily loaded systems and/or in the presence of external interference.

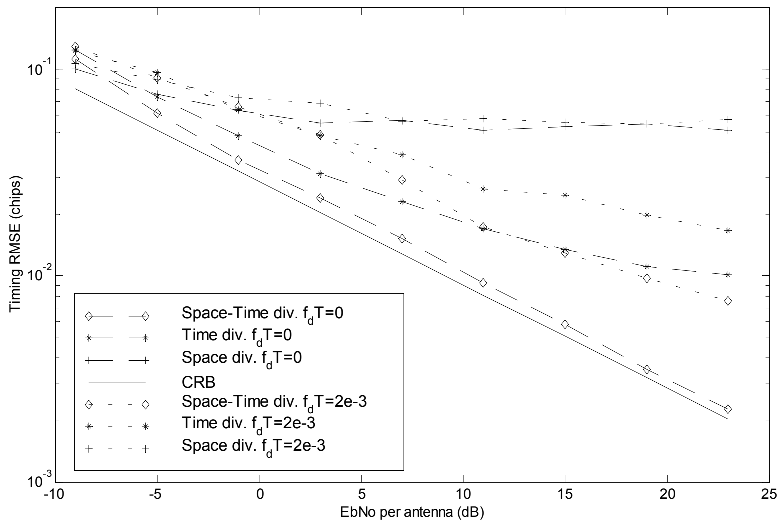

Figure 5: Performance of the estimators using space-time diversity, time diversity and space diversity as a function of the EbNo in two different channels. Parameters: M=80 bits, K=10 users, P=15chips/bit, m=4 antennas, NFR=10dB.

The contributions of this part of the thesis have been published in the references 1, 5, 7 and 9 of the list of publications.